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The similarity of life across the universe

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ABSTRACT Is the hypothesis correct that if life exists elsewhere in the universe, it would have forms and structures unlike anything we could imagine? From the subatomic level in cellular energy acquisition to the assembly and even behavior of organisms at the scale of populations, life on Earth exhibits characteristics that suggest it is a universal norm for life at all levels of hierarchy. These patterns emerge from physical and biochemical limitations. Their potentially universal nature is supported by recent data on the astrophysical abundance and availability of carbon compounds and water. Within these constraints, biochemical and biological variation is certainly possible, but it is limited. If life exists elsewhere, life on Earth, rather than being a contingent product of one specific experiment in biological evolution, is likely to reflect common patterns for the assembly of living matter.

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INTRODUCTION

There is a tendency to claim that our imaginations are limited in addressing the age-old question, "Are we alone in the universe?" That life-forms elsewhere, if indeed they exist at all, would have characteristics outside our own limited biochemical repertoire is a popular trope of science fiction. A good example of the hypothesis that the parameter space for the structure of life is wide is a collection of hypothetical organisms on other planets in our solar system as depicted in the *Atlas of Our Universe* (Gallant, 1986). One such organism, the Oucher-Pouchers, live on Venus and are essentially bags of gas. They bounce around on the surface of the planet, propelling themselves from one location to the next. The surface is hot (460°C), and so each time they bounce onto the rocks, they let out an excruciated noise that sounds like "ouch." They gather their bio-essential elements from rocks (sometimes feasting on the rare remains of old Soviet landers), and they have biochemical systems adapted to making a living on Venus in the absence of liquid water. The underlying hypothesis behind these creatures is that biochemistry will simply adapt to any planetary conditions it encounters.

However, from the subatomic to the macroscopic scale, life on Earth exhibits general characteristics that one can argue are universal. This hypothesis—that the architecture of life at all scales is limited—is the one I suggest here. It leads to testable predictions. For

example, it predicts that Venus is lifeless because there is no liquid water on the surface to act as a solvent for biochemistry. Spacecraft observations, albeit limited (e.g., Figure 1) are currently consistent with this prediction, at least with respect to potentially observable multicellular life. This is one datum point, and a countervailing argument could be that Venus is an end-member example of a completely uninhabitable environment. However, I suggest that if it is an end member, it is part of a data set that shows the limited range of potentialities for life. The observations of other planetary bodies in our solar system (one of which, Mars, is less extreme than Venus and yet does not appear to have present-day multicellular life either) do not currently refute this view.

SIMILARITY AT THE SUBATOMIC LEVEL

One of the most fundamental processes that life must be able to carry out is the acquisition of free energy from the environment to repair, grow, and reproduce—in other words, to maintain itself out of equilibrium with entropic processes that would tend to dismantle it. On Earth, to acquire energy, cells move electrons through a membrane from an electron donor or free electrons to an electron acceptor, in the process pumping protons (or in some cases, Na⁺ ions; Skulachev, 1991) across a membrane to generate the motive force that is used to produce the energy-containing molecule adenosine triphosphate (Mitchell, 1961). This occurs at the cell membrane or membranes within organelles. It is not inconceivable that electrons might be replaced by something else, but the use of electron donors and acceptors links energy production in life to a variety of widely available compounds from organic carbon to minerals in the planetary crust, such as iron and sulfur.

Under the process of environmental selection, there is an enormous adaptability to be had in using electrons to drive

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FIGURE 1: The surface of Venus appears dead to multicellular life (e.g., as imaged by Venera 13 and 14 in 1982), as we would predict based on the requirements of terrestrial life. There is as yet no evidence for organisms using entirely novel biochemistries adapted to this environment. (Images from USSR satellites, in the public domain.)

proton (or other) gradients. Life-forms that can use electron donors and acceptors as the basis of energy acquisition are likely to persist and proliferate on rocky planets in a wide diversity of habitats. The use of starlight (Bryant and Frigaard, 2006) to drive biochemistry (phototrophy) is also likely to be a universally successful way to gather energy (a process that itself involves energizing electrons), although many electron donors and acceptors provide independence from the need for starlight (Hoehler and Jørgensen, 2013). One could reasonably hypothesize that the use of the free energy available in subatomic particles (electrons) has a universal logic about it on account of the wide availability of electrons in the universe.

SIMILARITY AT THE ATOMIC AND MOLECULAR LEVELS

At the atomic level, the element used for assembling most compounds in terrestrial life (carbon) and much of the biochemistry that comes from it are probably universal (Pace, 2001). Carbon is versatile in building chains and rings and generating millions of permutations of compounds from which one can build life (Cockell, 2015). Science fiction writers have speculated about another element in group 14 of the periodic table—silicon—as an alternative. However, they forget that experiments in silicon chemistry have been occurring on the Earth since it formed.

A problem is that silicon, when brought into combination with oxygen, which is also a cosmically common element, has a tendency to form a huge variety of silicates (Liebau, 1985) that make rocks. If you have visited a good geology museum, you will know that there is a quite dizzying array of silicate minerals that in a crude way reflect the vast number of carbon compounds. These compounds are rather inert. Our planet and others show that silicon is the stuff of planetary geological diversity, not biochemical diversity.

Carbon is ubiquitous in the universe. A large variety of carbon compounds have been found in the interstellar medium (McBride et al., 2013). The monomers of the four major classes of biological macromolecules—amino acids, components of lipids, nucleobases, and individual sugars—have been found in carbon-rich meteorites (Sephton, 2002; Martins et al., 2008), formed in the protoplanetary disk from which our solar system emerged (Marty et al., 2013). Although it would be inviting trouble to completely rule out some

specific chemical conditions in or on a planet somewhere in the universe that might produce life that uses a different element, biochemical and, more recently, astrochemical information show that the use of carbon compounds to build living matter seems unsurprising.

Other molecules essential to terrestrial life have universal qualities. The solvent used for carrying out cellular reactions—water—like carbon, is abundant across the known universe (Mottl et al., 2007). When rocky planets form around stars, they, like Earth, have a tendency to condense large quantities of liquid water. This solvent has many of the characteristics useful for doing chemical reactions (it dissolves polar and small nonpolar compounds), it has a broad temperature range as a liquid that corresponds to the temperature conditions within, and in some cases on, planetary surfaces, and it is universally available. Suggested alternatives such as ammonia cannot

be completely ruled out, but the chemical characteristics of water and the more recent confirmation of its vast cosmic abundance make its use in life again perhaps unsurprising and probably common, maybe ubiquitous, if life exists elsewhere.

SOME BIOCHEMICAL VARIETY, BUT PROBABLY NOT MUCH

The molecules that are responsible for implementing the processes occurring in life, such as energy acquisition, can probably be constructed in a variety of ways. For example, the information storage system might be assembled alternately from the one we know on Earth, even using the same building blocks. A genetic code that has a three-base codon but only uses three nucleobases would still, with 27 combinations, allow for 20 amino acids and start and stop codons, albeit with less degeneracy than our code. The replacement of nucleobases in natural DNA with alternatives has allowed for the artificial creation of cells with different genetic codes (Malyshev et al., 2014), although in this case, the sugar-phosphate backbone and the fundamental way in which this code is read are maintained.

For proteins, in principle, there seems no reason why some of the 20 primary amino acids in life might not be replaced by some of the very large number of alternatives that exist in nature, such as in meteorites (>60 amino acids have been found in certain carbonaceous meteorites). It would be naive to suggest that the detailed molecular arrangements in biomolecules must be universal—and in this we might find variety. However, for reactions to be carried out in enzymes, there are biophysically optimal arrangements of charges in active sites that allow for electrons to be transferred and chemical reactions to be carried out. Like the extraordinary diversity of chassis that surround the otherwise globally similar internal combustion engine, biochemistry allows for variety, but at its core, it is constrained by the functions it must perform.

CELLULARITY

At the next hierarchical level of biology, the cell, we might suggest that compartmentalization through cellular structures is fundamental. A membrane concentrates solutes and macromolecules sufficiently to bring them into contact with each other and allow

reactions within a controlled chemical environment (Martin and Russell, 2003). A semipermeable structure to hold in molecules but allow communication with the outside environment seems a universal solution to the problem of chemical dilution.

Cell compartmentalization allows for constancy in the biochemical environment in otherwise physically and chemically diverse environments. It is therefore successful with respect to the capacity for cells to colonize a large number of environments across and within a planet. Viruses, a potential noncellular alternative, have no cellular structure, but they are generally biologically inert until they can be activated within the milieu of a fluid.

BUILDING MULTICELLULAR ORGANISMS

Moving from the cell to higher levels of organization, there remains a universal logic. How can individual cells cooperate to be more successful in reproducing and thus resulting in a planet harboring life over geological timescales? Either the cells interact as free-living organisms like many of the multicellular traits in bacteria (Shapiro, 1998), or they cooperate to such a degree that they differentiate (merely a form of division of labor), leading to that branch of life we call “multi-cellular” (but which is distinguished from the “multicellular” behaviors of microorganisms by true cellular differentiation).

The form into which these multicellular organisms are molded by evolution is limited by physics. To exist in the ocean, hydrodynamics comes into play, and to fly, aerodynamics takes control. The endpoint of these multicellular forms can be diverse. Flying organisms range from a 0.15-mm-sized fairyfly, the smallest winged insect, to the 20-m wingspan of the extinct pterodactyl, *Quetzalcoatlus*. However, convergent evolution (Conway-Morris, 2005), driven by physical requirements, limits the true scope of the “unlimited” possibilities at the macroscopic scale beloved of science fiction writers.

SIMILARITY AT THE POPULATION LEVEL

At the scale of the populations of organisms, the organization of biology follows simple rules. Variation is generated within organisms. Some of these are better adapted to the environment than others and reproduce. Some of them die. This is the process of Darwinian evolution (Darwin, 1859), and although one can argue about the minutiae of microevolutionary and macroevolutionary biology, the basic idea that the environment selects successful organisms, which then go on to reproduce, resulting in evolution in response to changing planetary conditions, would seem to be applicable to any planet with life-forms that have finite lifespans living in environments that change. As some of these organisms get isolated or separated, different environments in which they live will cause speciation.

The long-term result of this emerging complexity as a biosphere develops is the Linnaean system of hierarchy, in which a given organism has relatives that can be identified in larger groupings with common ancestors. On Earth, this hierarchy can be quantified using phylogenetic trees (Delsuc *et al.*, 2005). There may be complications—an example is horizontal gene transfer, which blurs the clarity of the vertical transmission of information from one generation to the next. However, emerging complexity leading to hierarchies of organisms that share common ancestors is likely to be a universal characteristic of life. We can expect phylogenetic trees (or their alien equivalent, whatever the biochemical nature of information storage) to exist on other planets.

Even the *behavior* of populations of organisms is likely to be guided by principles that can be applied universally. The

developing branch of physics called “active matter” investigates the interactions of particles (or organisms, as is the case here) under nonequilibrium conditions. It is increasingly being applied to cellular and organismal systems—when bacteria swarm or starlings flock, for instance. Models can predict optimal bird flocking behaviors that fit with observation (Chazelle, 2014). If we could ever observe the murmurations of flying creatures in the skies of an alien world, the patterns they exhibit would probably be similar, or at least governed by the same rules, that we will have elaborated for the behavior of populations of organisms on Earth.

CONCLUSION

The processes carried out by, and the general features of, life on Earth are probably universal. The movement of subatomic particles to generate energy through to the taxonomic hierarchies of life seem to be the product of the constraints of physics, biochemistry, emergent complexity, and the astrophysical abundances of compounds. Alien biospheres, if they exist, are likely, across the hierarchy of biological architecture, from the subatomic to the population level, to mirror much of the fundamental features of terrestrial biology.

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